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Role of land-atmosphere coupling in summer droughts and floods over eastern China for the 1998 and 1999 cases

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Droughts and floods are the two most costly climate disasters over China. However, our ability to predict droughts and floods is limited by poor understanding of the atmospheric response to long memory climate drivers such as sea surface temperature and soil moisture. In this study, we investigate soil moisture feedbacks on summer droughts and floods over eastern China for the 1998 and 1999 cases using the Weather Research and Forecasting (WRF) model simulations. Soil moisture climatology, derived from a 20-year-long control run, is used to replace soil moisture evolution in uncoupled simulations for 1998 and 1999 summers. Eastern China experienced severe floods during the summer of 1998, while 1999 summer is characterized by a "southern flood and northern drought" pattern. The WRF model generally simulates relatively well the droughts and floods in the two summers. It is found that land-atmosphere coupling contributes substantially to both droughts and floods over northern China while it plays a relatively small role in precipitation anomalies over southern China. Our findings suggest that soil moisture memory help contribute skill to seasonal prediction of droughts and floods over northern China.

soil moisture feedbacks, climate disasters, droughts, floods, regional climate modeling

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Droughts and floods are the two most devastating climate disasters over China and pose serious threats to sustainable development of economy and society [1,2]. An exceptional example is the 1998 flood over the Yangtze River valley, which took 1320 lives and affected 223 million people, damaged approximately 2×10^6 hm^2 croplands, and caused a large economical loss of about 166.6 billion Yuan [3]. The floods also hit many other areas in the summer of 1998, and the Yangtze River valley again in the summer of 1999. Many areas of northern China experienced droughts in the summer of 1999, which caused severe societal and economical losses [4]. Droughts and floods over China have been found to have an increasing trend over last several decades [5,6].

The occurrence of summer droughts and floods over eastern China is closely related with East Asia summer monsoon (EASM) system. Previous studies have explored physical mechanisms for severe floods in the summer of 1998. 1997/1998 El Niño-Southern Oscillation (ENSO) cycle is the strongest El Niño event in the 20th century, and 1998 summer is in the decaying stage of the ENSO event [1, 7–10]. Also, the Tibetan Plateau experienced extremely heavy snowfall in the winter of 1997 and the spring of 1998 [1,7,9]. In addition, the sea surface temperature in the sublayer of the western Pacific warm pool was in a cooling state [1,7,9,10], the convective activities around the Philippines were weak [1,7,9,10], the western Pacific subtropical high shifted southward [1,7,9–11], and water vapor was much strongly transported from the Bay of Bangle, the South China Sea, the tropical western Pacific and tropical Indian Ocean into eastern China [7,9,10,12]. In the summer of 1999, floods occurred over South China and severe and

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prolonged droughts appeared over North China. 1999 experienced a strong La Niña event [13,14]. Heat source over the Tibetan Plateau showed late establishment and reduced intensity [15,16]. 1998–1999 sea surface temperature over the region from South China Sea to the tropical western Pacific was highest during 1981–2000, the western North Pacific subtropical high significantly shifted eastward, and the southwesterly airflows from the Bay of Bengal and tropical Indian Ocean extended eastward [13,15]. In addition, northward propagation of 30–60-day mode collapsed around 20°N and anomalous circulation over the Eurasia was persistent in the summer of 1999 [14,17]. The South China Sea summer monsoon was about ten days later onset and the EASM was weak northward advance [15,17]. The anomalies subsequently contributed to droughts and floods in the summer of 1999.

An anomaly in soil moisture can alter latent heat flux and other surface energy balance components, and subsequently influence the climate at a variety of time and space scales [18–24]. Some previous studies have explored the effects of soil moisture on summer climate over China or East Asia [25–32]. Regional climate models have been found to have better ability to simulate land-atmosphere interactions and regional characteristics compared to atmospheric general circulation model [33–43]. Several studies have previously used regional climate models to investigate the role of initial soil moisture in 1998 floods and 1999 droughts over eastern China. For example, Kim and Hong [44] used the National Centers for Environmental Prediction Regional Spectral Model to examine the impacts of initial soil moisture on 1998 summer precipitation over East Asia. Chow et al. [45] discussed the effects of initial soil moisture in the Tibetan Plateau during the spring period on 1998 summer precipitation over eastern China by using a regional climate model. Hu et al. [46] explored the importance of initial soil moisture to 1998 summer precipitation simulations over eastern China with the Beijing Climate Center regional climate model (BCC-RegCM). These regional climate model simulations of soil moisture impacts mainly focused on the role of initial soil moisture conditions in summer floods and droughts, and found that initial soil moisture conditions contribute to droughts and floods to some degree over eastern China. In this study, we investigate summertime soil moisture feedbacks on droughts and floods over eastern China for the 1998 and 1999 cases with the Weather Research and Forecasting (WRF) model coupled with the Noah land model.

1 Approach

This study uses the National Center for Atmospheric Research WRF model with the advanced research WRF (ARW) dynamics solver. The model has been applied to the United States and East Asia [23,47–49], and found to simulate climate mean and variability realistically in diverse climate regimes. This study uses WRF version 3.1.1 coupled with unified Noah land model with four soil layers with thicknesses of 10, 30, 60, and 100 cm from the top to down. Model set includes 60-km horizontal grid resolution (8160 km (west-east) ×5760 km (south-north), centered at 36°N and 116°E), and 28 vertical layers. The model is driven with the National Centers for Environmental Prediction (NCEP)-Department of Energy (DOE) reanalysis II. Please refer to Zhang et al. [47] for more details of model configuration.

The control run (CTL) includes a 21-year-long simulation with interactive soil moisture, covering the period of January 1979 to December 1999. Two additional simulations repeat 1998 (98SoilM) and 1999 (99SoilM) summer integrations with the same model setup, except that we replace soil moisture value at each time step using the climatology of CTL. 98SoilM and 99SoiM uncouple interactive soil moisture, and its differences with CTL can be used to quantify the role of land-atmosphere coupling in droughts and floods during the summers of 1998 and 1999.

2 Results

Figure 1 presents observed 1998 and 1999 summer precipitation anomalies with respect to 1980–1999 climatology over eastern China. The observational precipitation data are taken from the East Asia gauge-based analysis [50]. Most of eastern China experienced positive precipitation anomalies in the summer of 1998. Particularly large positive anomalies are found over the Yangtze River valley, the lower reach of the Yellow River valley, and western part of Northeast China. In the summer of 1999, negative precipitation anomalies appeared over most of the areas north of about 30°N while southern China exhibited positive precipitation anomalies. Over many areas in both years, the anomalies are larger than 30% of 1980–1999 summer means.

The WRF model generally simulates precipitation anomalies over eastern China relatively well in the two summers both in the magnitude and spatial pattern while soil moisture is allowed to interact with the atmosphere in CTL (Figure 2(a) and (d)). The model biases also should be noted. The simulated centers of large positive precipitation anomalies are displaced slightly to the south in the summer of 1998. The WRF model simulates smaller geographic scope of negative precipitation over northern China in the summer of 1999.

We further compare CTL against the two additional experiments without interactive soil moisture to isolate soil moisture feedbacks on droughts and floods over eastern China. In the summer of 1998, the floods reproduced by CTL over the areas north of 35°N are largely missed in the experiment with prescribed climatological soil moisture (Figure 2(a)–(c)), particularly over many areas of the

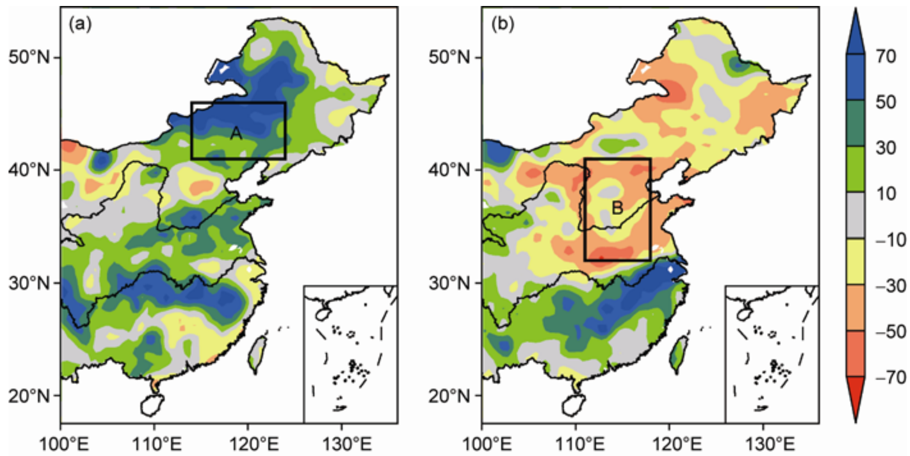

Figure 1 Observed summer precipitation anomalies (%) relative to 1980-1999 summer climatology. (a) 1998; (b) 1999. The two black boxes cover areas of 114°–124°E and 41°–46°N (Region A) in (a), and 111°–118°E and 32°–41°N (Region B) in (b), respectively.

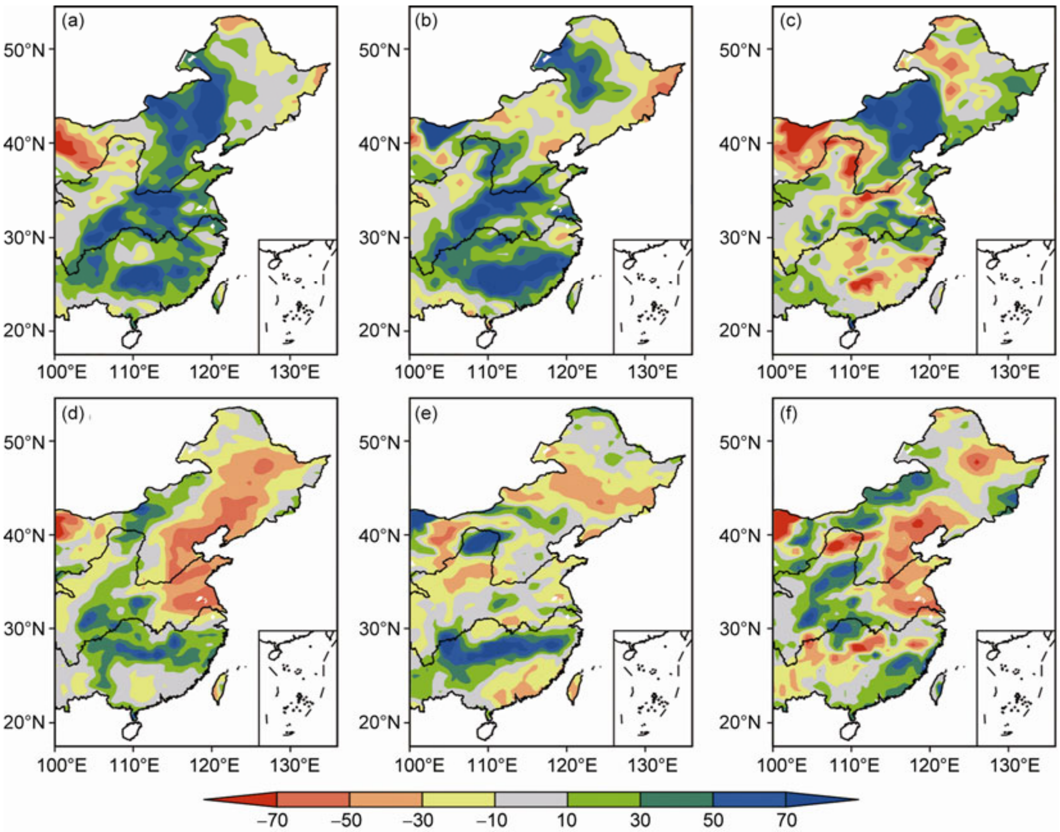

Figure 2 Soil moisture feedbacks on precipitation anomalies in the summers of 1998 (top) and 1999 (bottom). (a), (d) simulated summer precipitation anomalies relative to 1980–1999 summer climatology in CTL; (b), (e) simulated summer precipitation anomalies relative to 1980–1999 summer climatology in 98SoilM and 99SoilM; (c), (f) precipitation differences between CTL and uncoupled experiments (CTL minus 98SoilM, and CTL minus 99SoilM).

climatic and ecological transition zone (Region A in Figure 1(a)). In the summer of 1999, the droughts over northern China (Region B in Figure 1(b)) are only seen in CTL (Figure 2(d)–(f)). The results indicate that land-atmosphere coupling plays a critical role in influencing both droughts and floods over northern China. In contrast, over southern China during both summers, the floods can be captured in both CTL and the experiments without interactive soil moisture. The results are not unexpected. Previous studies have demonstrated that land-atmosphere coupling is generally weak over humid southern China, and has small impacts on surface evapotranspiration and precipitation [23,47,51].

Since large differences in summer precipitation anomalies between CTL and SoilM mainly appear over Regions A and B, in the following investigation we focus on the two regions to explicitly explore the role of soil moisture in floods and droughts. Firstly, we evaluate the ability of WRF model to reproduce the floods in the summer of 1998 over Region A and the droughts in the summer of 1999 over Region B. The averaged summer precipitation anomalies relative to 1980–1999 in observation and CTL are 50.4% and 60.0% in 1998 over Region A and –34.2% and –30.1% in 1999 over Region B, indicating that the WRF model simulates relatively well the floods and droughts. Next, we compare summer precipitation anomalies in CTL and SoilM to investigate the role of soil moisture in the floods and droughts over the two regions. In the summer of 1998, the averaged summer precipitation anomaly in SoilM is only 4.1%. The difference of 55.9% between CTL and SoilM indicates that soil moisture is a leading factor to influence the floods. In the summer of 1999, the averaged summer precipitation anomaly over Region B in SoilM is −11.6% and thus the difference between CTL and SoilM is 18.5%, implying soil moisture plays a substantial role for the droughts.

We further compare daily precipitation in CTL and SoilM in the summer of 1998 averaged over Region A and in the summer of 1999 averaged over Region B (Figure 3). In the summer of 1998, daily precipitation in CTL is larger than that of SoilM over Region A on many days. In particular, large differences are seen in middle and heavy precipitation (⩾10 mm/d): frequency of middle and heavy precipitation in CTL is 20 while it is only 7 for soilM. The result demonstrates that soil moisture influences the floods over Region A in the summer of 1998 mainly through its effects on middle and heavy precipitation. In contrast, the precipitation differences between CTL and SoilM in the summer of 1999 over Region B are mainly reflected by changes in light precipitation (<10 mm/d): frequency of light precipitation in CTL is smaller than that of SoilM on many days. The reduction of light precipitation frequency has been reported to lead to the occurrence of droughts [52–55].

The observations of soil moisture over China are limited in time and space [29,56]. The Global Land Data Assimilation System (GLDAS) [57] soil moisture product has been shown to have a good agreement with *in situ* measurements over eastern China [58]. Figures 4 and 5 present 1998 and 1999 summer soil moisture anomalies relative to 1980–1999 summer climatology at soil layers of 0–10, 10–40, 40–100 and 100–200 cm from the GLDAS soil moisture product and the WRF model, respectively. Generally, the WRF model can reproduce soil moisture anomalies in the summers of 1998 and 1999 relatively well though some biases remain. In the summer of 1998, both the GLDAS soil moisture and WRF model display large positive anomalies over Region A at three soil layers of 0–10, 10–40, and 40–100 cm (Figure 4).

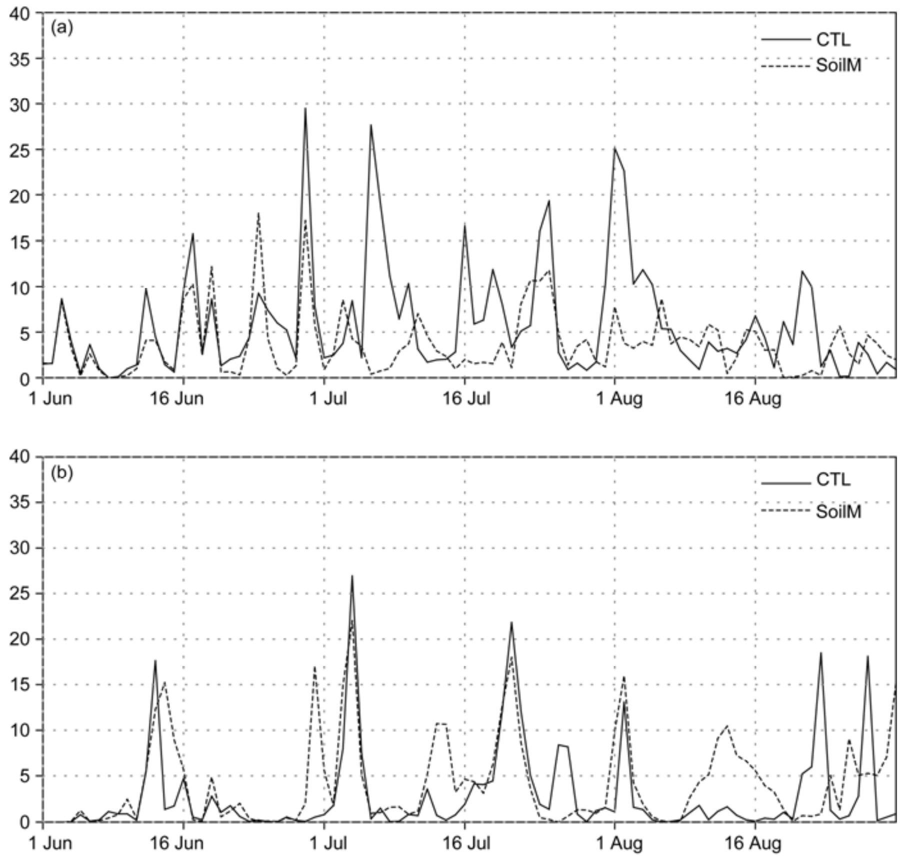

Figure 3 Daily precipitation (m) averaged over Regions A and B in Figure 1 for CTL and SoilM in summers of (a) 1998; (b) 1999.

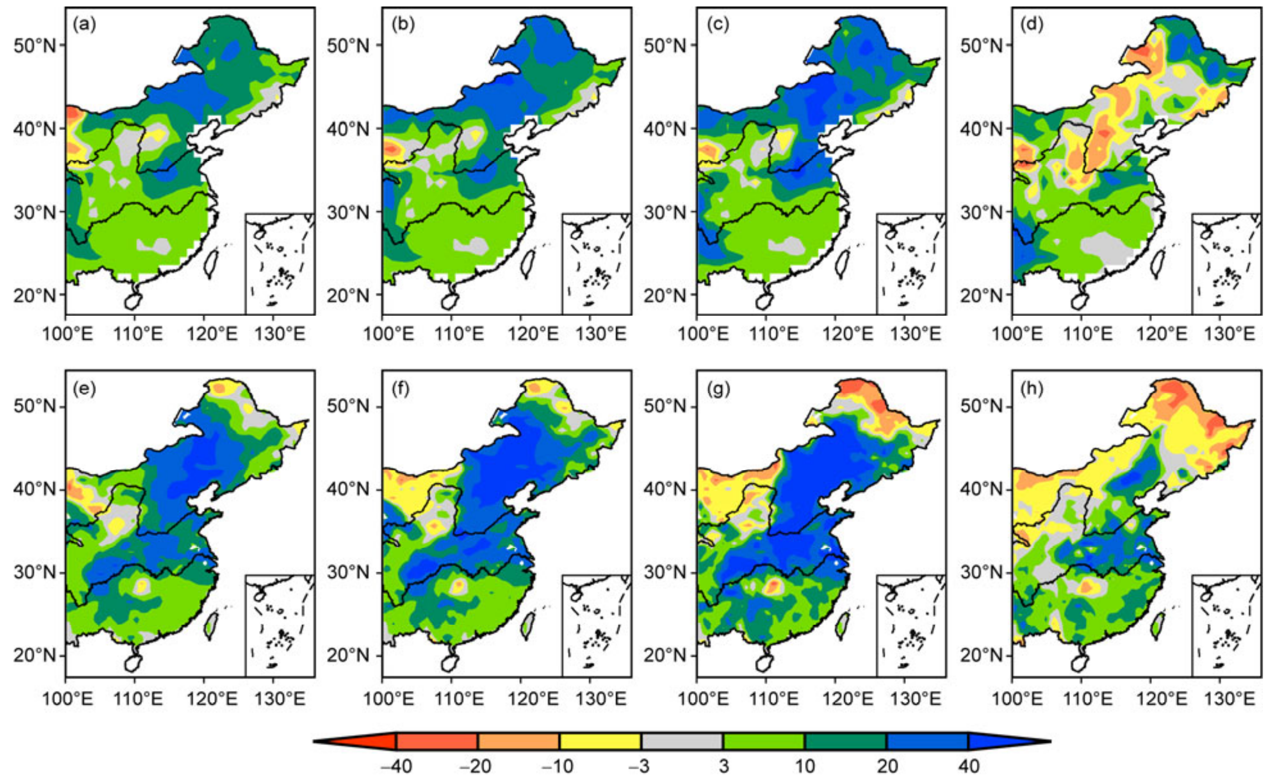

Figure 4 Summer soil moisture anomalies (%) in 1998 relative to 1980–1999 summer climatology at soil layers of 0–10 cm ((a),(e)), 10–40 cm ((b),(f)), 40–100 cm ((c),(g)), and 100–200 cm ((d),(h)) in the GLDAS soil moisture product from the Noah model (top) and WRF model simulations (bottom).

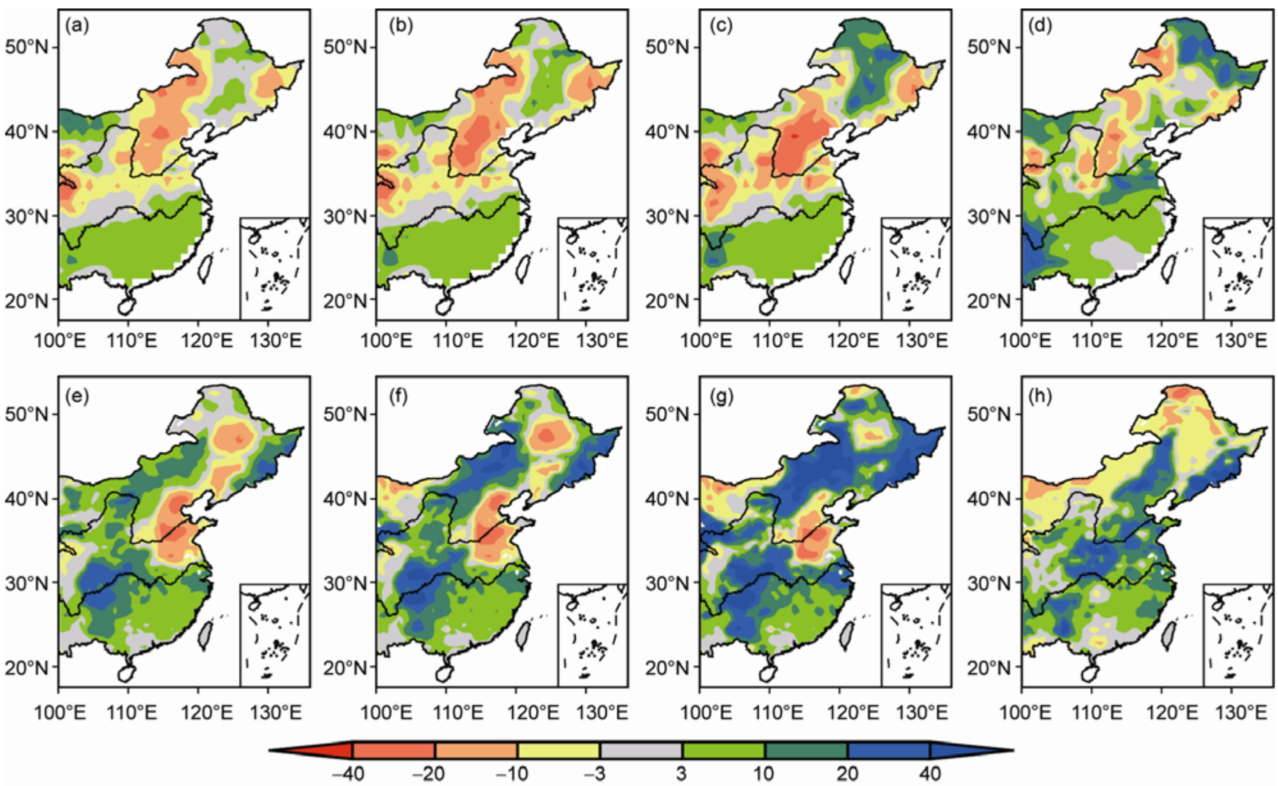

Figure 5 Summer soil moisture anomalies (%) in 1999 relative to 1980–1999 summer climatology at soil layers of 0–10 cm ((a), (e)), 10–40 cm ((b), (f)), 40–100 cm ((c), (g)), and 100–200 cm ((d), (h)) in the GLDAS soil moisture product from the Noah model (top) and WRF model simulations (bottom).

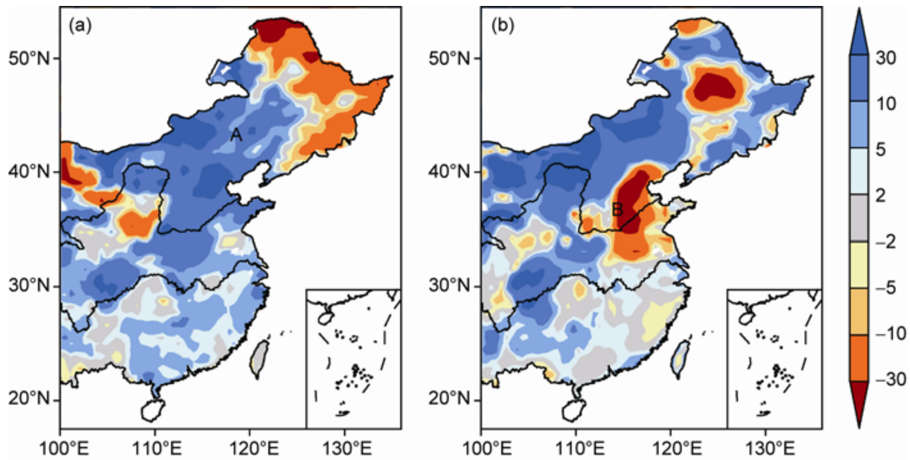

Figure 6 Simulated summer latent heat anomalies (%) relative to 1980–1999 summer climatology. (a) 1998; (b) 1999.

The positive soil moisture anomalies result in positive latent heat flux anomalies over Region A (Figure 6(a)), which subsequently lead to the floods. In the summer of 1999, large negative anomalies in the GLDAS soil moisture product are found over Region B at soil layers of 0–10, 10–40, and 40–100 cm (Figure 5(a)–(d)), which are successfully reproduced by the WRF model (Figure 5(e)–(h)). The negative soil moisture anomalies over Region B lead to negative latent heat flux anomalies (Figure 6(b)), which are largely responsible for the droughts. We note that over some areas large latent heat anomalies induced by soil moisture do not lead to large precipitation anomalies. That is not unexpected since previous studies have demonstrated that soil moisture feedbacks on summer precipitation depend on climate regimes [23,47].

3 Conclusions

Droughts and floods which occurred frequently in China, can have dramatic impacts on agriculture, water resources, ecosystems, and human welfare. However, our ability to predict droughts and floods remains poor, limiting our adequate society adaptation. Low prediction skills of droughts and floods are, to a large extent, due to our limited understanding of land-atmosphere interactions. This study investigates the role of land-atmosphere coupling in summer droughts and floods for the 1998 and 1999 cases using the regional climate simulations with the WRF model. The control run consists of a continuous run for 1979–1999 with a fully coupled Noah land model while two additional experiments uncouple soil moisture evolutions, covering the summers of 1998 and 1999, respectively. We use precipitation differences between the control run and the two additional experiments to isolate soil moisture feedbacks on droughts and floods for the two summers.

In observations, eastern China generally experienced positive precipitation anomalies in the summer of 1998, with the anomalies more than 30% of 1980–1999 summer means appearing over the Yangtze River valley, the lower reach of the Yellow River valley, and western part of Northeast China. The 1999 summer is characterized by negative precipitation anomalies over northern China and positive precipitation anomalies over southern China. The WRF model generally simulates precipitation anomalies relatively well in both the magnitude and spatial pattern in the two summers. Meanwhile, the model bias should be noted. Giorgi and Bi [59] demonstrated that the effect of initial conditions on summer precipitation bias can reach 5%–10% of the average precipitation at the subregional level. Since our simulations are based on one initial condition, ensemble experiments with different initial conditions should be conducted to reduce the model biases in the future. Also, the model biases may be related with deficiencies in the internal model physics and numerics, choices of model resolution and domain, and inaccuracy of large-scale driving fields. More studies are clearly needed to clarify these issues.

Without interactive soil moisture, the WRF model cannot, to a large extent, capture both droughts and floods over northern China. However, that is not the case for southern China. Precipitation anomalies over southern China can be reproduced in the simulations both with and without interactive soil moisture. The results indicate that soil moisture plays a substantial role in northern China droughts and floods while it has a relatively small ability to affect precipitation anomalies over southern China. Our findings suggest that the memory inherent in soil moisture can help improve prediction skills of summer droughts and floods over northern China, even in El Niño/La Niña years.

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